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National Aeronautics and
Space Administration

# MATERIALS FOR ADVANCED TURBINE ENGINES

## PROJECT COMPLETION REPORT
## PROJECT 1

## POWDER METALLURGY RENÉ 95 ROTATING TURBINE ENGINE PARTS

Volume 2

by

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**16. Abstract**


This report presents the results of engine testing of a René 95 alloy as-HIP high pressure turbine aft shaft in the CF6-50 engine and a HIP plus forged René 95 compressor disk in the CFM56 engine. The CF6-50 engine test was conducted for 1000 "C" cycles and the CFM56 test for 2000 "C" cycles.

Posttest evaluation and analysis of the CF6-50 shaft and the CFM56 compressor disk included visual, fluorescent penetrant, and dimensional inspections. No defects or otherwise discrepant conditions were found. These parts were judged to have performed satisfactorily.

The results reported represent work performed on Tasks IV and V of MATE Project 1 and are presented as FEDD Category 2 data. Work performed on Tasks I, II, and III of Project 1 is presented in NASA Report No. CR-159802.


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# 1.0 SUMMARY

The purpose of this program was to develop manufacturing procedures for producing near-net-shape René 95 alloy parts using powder metallurgy processes. The overall objective was to achieve significant cost reductions as compared to conventional ingot metallurgy processes by using hot isostatic pressing (HIP) of argon atomized powder near-net shapes or by HIP of preforms followed by hot die or isothermal forging (HIP plus forge) processes. The CF6-50 high pressure turbine aft shaft was selected to demonstrate the as-HIP processes, and the CFM56 compressor rotor disk (Stages 5 through 9) was selected for demonstration of the HIP plus forge processes. Each of these processes was successfully developed during Tasks I, II and III of Project 1. The mechanical properties obtained met the requirements for engine test of the selected parts in CF6-50 and CFM56 engines.

The as-HIP high pressure turbine rotor (HPTR) aft shaft was successfully engine tested for 1000 standard endurance test cycles in the CF6-50 engine, and the HIP plus forged compressor disks were successfully engine tested in the CFM56 engine for 2000 endurance cycles. Both of these engine tests were land-based tests in test cells at test conditions which simulated typical operating conditions for these engines. The engine tests were followed by posttest evaluations which included visual, fluorescent penetrant, and dimensional inspections. No defects or otherwise discrepant conditions were detected and the parts were judged to have successfully completed the endurance testing and were judged acceptable for further engine operation.

# 2.0 INTRODUCTION

## 2.1 BACKGROUND

The NASA-MATE Program has as its primary objective the introduction of new materials' technologies into advanced aircraft turbine engines to more rapidly achieve economic and performance advantages. The program encompasses the accelerated transfer of selected materials' technologies by scaling them up from the feasibility stage to engine demonstration.

The first MATE project conducted by the General Electric Company involved the scaleup of powder metallurgy processes for the manufacture of advanced aircraft gas turbine engine components using the René 95 nickel-base alloy. The following paragraphs describe some of the characteristics of this alloy together with the objectives of the MATE project effort.

Of the wrought nickel-base superalloys used for turbine and compressor disks, shafts, rotating seals, and related parts, René 95 is the strongest of the commercially available superalloys over the use temperature range from ambient to about 650° C (1200° F). Table I shows the specified composition for the René 95 alloy. The superior strength of René 95 resulted in its selection as the material of choice for hot rotating parts in several advanced development and production engines at General Electric. The alloy is used today in the CFM56, F101, T700, and F404 engines which have been selected to power various fighters, helicopters, and transport aircraft. Components utilizing the René 95 alloy include the Stage 4 through 9 compressor disks, the high pressure turbine disk, aft compressor stub shaft, and the high pressure turbine forward shaft in the CFM56 and F101 engines. René 95 is also used for the high pressure turbine disks (two stages) and associated cooling plates in the T700 engine. In the F404, René 95 is specified for four stages of aft compressor disks, the aft compressor shaft, the high pressure turbine disk with its associated blade retainers, and rotating seal.

The CFM56 engine has been selected to retrofit several first generation commercial jet aircraft with a more modern engine and is a candidate for powering several medium-sized commercial aircraft scheduled for production in the 1980's. A commercial version of the military T700 turboshaft engine, the CT700, will enter production in the near future.

The development of the René 95 alloy combined with the concurrent development of the inertia welding process made possible the design of the integral aft compressor spool of the CFM56 engine, comprising five individual disks inertia welded to one another to form the spool. The design of this spool was responsible for:

- The manufacture of five compressor disk stages from a forged shape of one configuration
- Common tooling for fabricating and inertia welding these stages

Table I. René 95 Powder Composition.

| Element | Weight % Alloy | |
|---|---|---|
| | Minimum | Maximum |
| C | 0.04 | 0.09 |
| Mn | --- | 0.15 |
| Si | --- | 0.20 |
| S | --- | 0.015 |
| P | --- | 0.015 |
| Cr | 12.0 | 14.0 |
| Co | 7.0 | 9.0 |
| Mo | 3.3 | 3.7 |
| Fe | --- | 0.5 |
| Ta | --- | 0.2 |
| Cb | 3.3 | 3.7 |
| Zr | 0.03 | 0.07 |
| Ti | 2.3 | 2.7 |
| Al | 3.3 | 3.7 |
| B | 0.006 | 0.015 |
| W | 3.3 | 3.7 |
| O | --- | 0.010 |
| N | --- | 0.005 |
| H | --- | 0.001 |
| Ni | Balance | Balance |

- The elimination of internal bolted flanges which in turn:
  - Reduced rotor weight
  - Reduced the number of component parts
  - Eliminated bolt hole stress concentrations
  - Increased rotor stiffness.

The exceptionally high strength and elevated temperature properties of René 95 permitted a large bore, thin web disk design, resulting in an exceptionally lightweight aft compressor spool.

René 95 was initially developed by General Electric under Air Force sponsorship. The original alloy development was performed using double vacuum melting with vacuum arc remelting as the final step. Forging and heat treating procedures were developed for René 95 to produce a unique microstructure by controlled forging processes for the arc-cast ingot known as the "necklace" structure. This structure consists of warm-worked grains surrounded by a necklace of fine recrystallized grains. René 95 with the necklace structure exhibited superior crack propagation resistance and notched low cycle fatigue strength as compared to fine grained material. Attainment of the necklace structure became a major requirement in forging and heat treating arc-cast ingots of René 95.

Parts made by conventional process technology cost about twice as much as similar parts made of lower strength alloys which were used for turbine and compressor rotating parts in earlier engines. This cost problem prompted the initiation of major cost reduction efforts on René 95 parts.

The cost reduction approach selected involved the use of high purity prealloyed René 95 argon atomized powder consolidated into shapes by hot isostatic pressing. Preforms made by HIP consolidation may be subsequently forged to near-finished size shapes or parts can be HIP'd directly to a near-net-shape (NNS) without using forging processes. Initial feasibility demonstration of the HIP plus forge approach was made using the CFM56 Stage 5 through 9 compressor disks as the demonstrator part. This work indicated that both processes (as-HIP and HIP plus hot die forging) could produce properties equivalent to those of conventional cast and wrought René 95.

The overall objective of the General Electric MATE Project 1 Program was to refine René 95 superalloy powder metallurgy processing technology to permit the fabrication of turbine engine rotating parts at significant cost reductions as compared to similar parts produced by more conventional methods. It was predicted that process technology advancements could be achieved which would permit cost reductions in such production engine parts of at least 50% as compared to conventionally processed René 95. These very significant cost reductions were to be achieved with the introduction of parts produced by hot die forging of hot isostatically pressed René 95 powder shapes as well as parts produced by HIP compaction alone (as-HIP).

The HIP and hot die forged René 95 powder parts were made by producing preforms which were then hot die forged and heat treated. The engine components chosen to demonstrate this latter technology were the Stages 5 through 9 disks of the CFM56 compressor rotor. Each of these compressor disks is machined and then inertia welded together using a common input forging.

As-HIP René 95 parts for Project 1 were also produced to minimum envelope shapes for replacement of certain conventionally forged and heat-treated Inconel 718 parts in the CF6-50 engine. The engine component chosen to demonstrate this technology was the CF6-50 high pressure turbine rotor rear shaft.

## 2.2 PROGRAM SCOPE

As reviewed briefly above, the initial technology scaleup project performed by the General Electric Company under the MATE Program was Project 1, "Powder Metallurgy René 95 Rotating Turbine Engine Parts." The objective of this project was to refine powder metallurgy processing of René 95 to permit significant cost reductions in rotating turbine engine parts compared to current practices. To demonstrate this technology, two turbine engine components were manufactured using related powder metallurgical processing methods. One component was the aft shaft of the CF6-50 engine high pressure turbine which was fabricated by hot isostatic pressing René 95 powder to near-final size followed by heat treatment. The second component was a compressor rotor disk for use in the fifth through ninth stages of the F101 and CFM56 engines. It was produced by hot-die forging of HIP René 95 preforms which were subsequently inertia welded and machined into a compressor rotor.

The Program Task structure of Project 1 was as follows:

Task I - Material Envelope Design

Task II - Process Development

Task III - Manufacturing

Task IV - Engine Test

Task V - Posttest Analysis

A flow chart showing the overall program structure is shown in Figure 1. Note that Tasks IV and V covered the engine testing reported here. The results of Tasks I, II and III are presented in Volume 1 of the final Project 1 report issued as NASA Report Number CR-159802 dated June 1979.

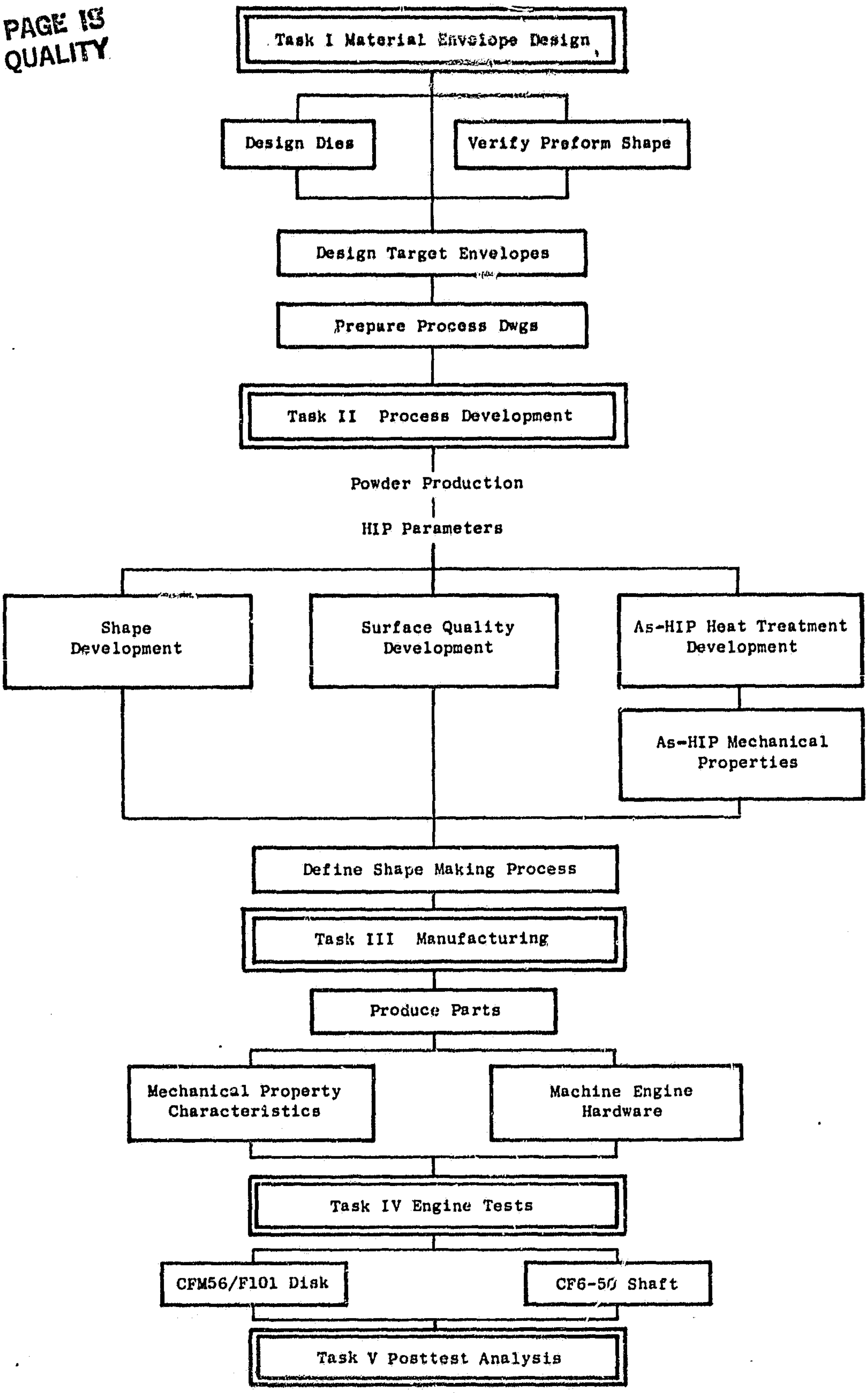


Figure 1. Powder Metallurgy René 95 Rotating Turbine Engine Parts.

# 3.0 ENGINE TEST PROGRAM

## 3.1 PREPARATION FOR ENGINE TEST

An as-HIP René 95 high pressure turbine rotor aft shaft for the CF6-50 engine was manufactured as described in Volume 1, CR-159802, of the final Project 1 report. The Part Number of this component was 4013194-111P01 and the Serial Number of the engine test part was SM587. The engine test was conducted in CF6-50 engine Serial Number 455-508/18. A photograph of the HPTR aft shaft component as finish-machined prior to engine test is shown in Figure 2. Figure 3 is a drawing showing the as-HIP target shape envelope and the finish machined shape.

HIP plus forged CFM56 engine Stage 5 through 9 compressor disks were manufactured from René 95 powder as described in Volume 1. The CFM56 engine test took place using engine Serial Number 502-008. Each of the Stage 5 through 9 compressor disks were forged to the same configuration and were therefore interchangeable. The individual disks are inertia welded to produce a Stage 4 through 9 integral shaft spool (Stage 4 is a different configuration and must be made from a different forging). The spool is Part Number 4013255-390, while individual Stage 5 through 9 disks are Part Number 4013084-314. The MATE engine spool assembly S/N 9707. The MATE engine test disk was the Stage 5 disk forging, Serial Number 27634, produced from master power blend 77032. Other disks from this powder blend and processing procedure were cut up and mechanical property evaluation was conducted as described in Volume 1.

Figure 4 is a drawing showing the as-forged and sonic machined configuration for these disks. A bore integral test ring is indicated at "T". Figure 5 shows two typical disks in the machined configuration for ultrasonic testing. Figure 6 shows the CFM56 spool in the as-machined configuration prior to engine test.

## 3.2 MECHANICAL PROPERTIES

The mechanical properties and other requirements representative of the parts engine tested here are discussed and presented in detail in Appendices A through F of Volume 1. Table II presents the target mechanical properties for the as-HIP CF6-50 HPTR aft shaft and Table III presents the target properties for the HIP plus forged CFM56 compressor disk. Test rings from both components met the indicated requirements as did cutup forgings from parts produced concurrently.

## 3.3 ENGINE TESTING

The CF6-50 HPTR aft shaft and the CFM56 compressor disks were engine tested under standard "C" cycle testing which simulates in a test cell the temperature, stress, and cyclic nature of actual engine operation on a commercial transport aircraft.

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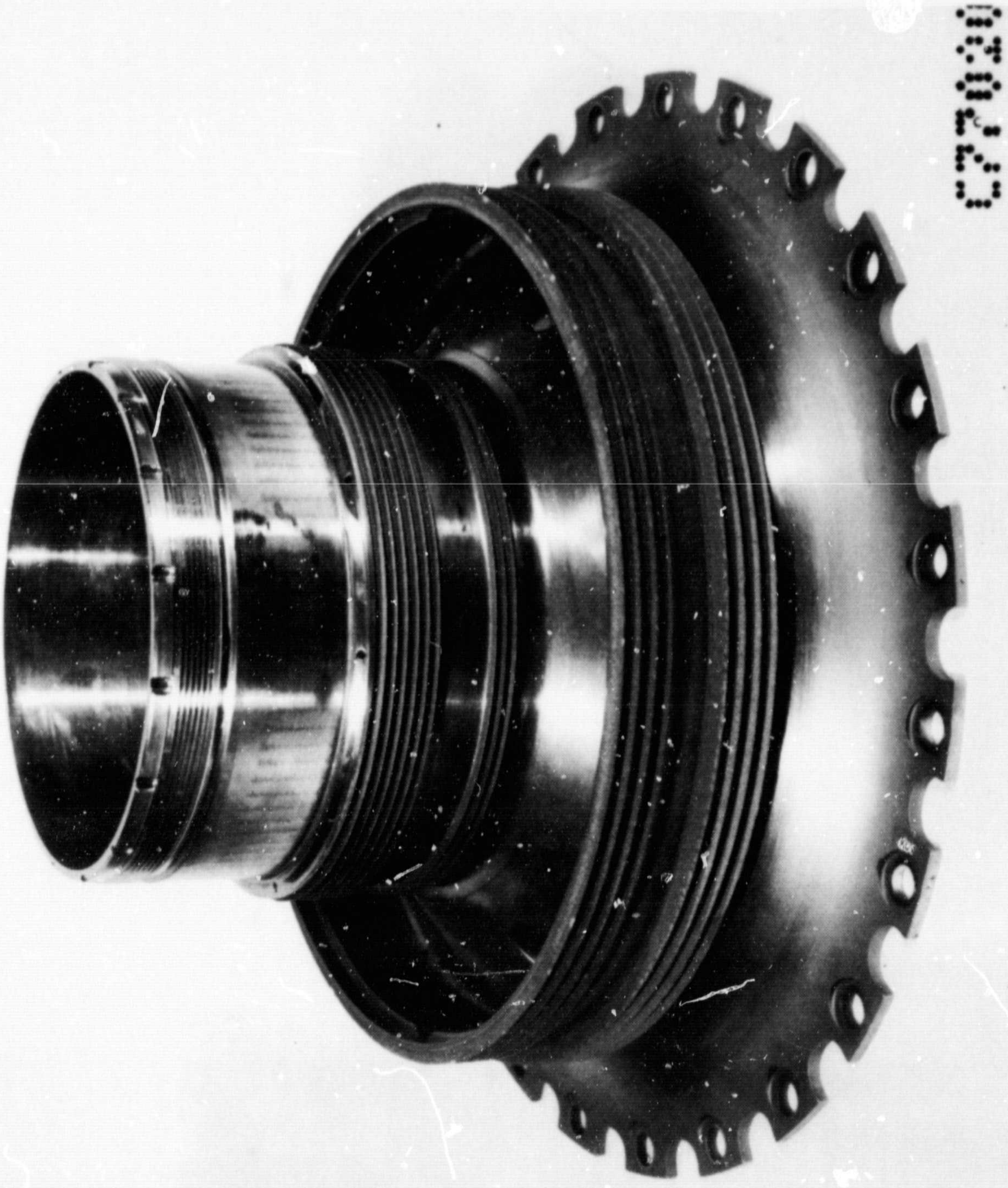

Figure 2. As-Machined High Pressure Turbine Rotor Aft Shaft.

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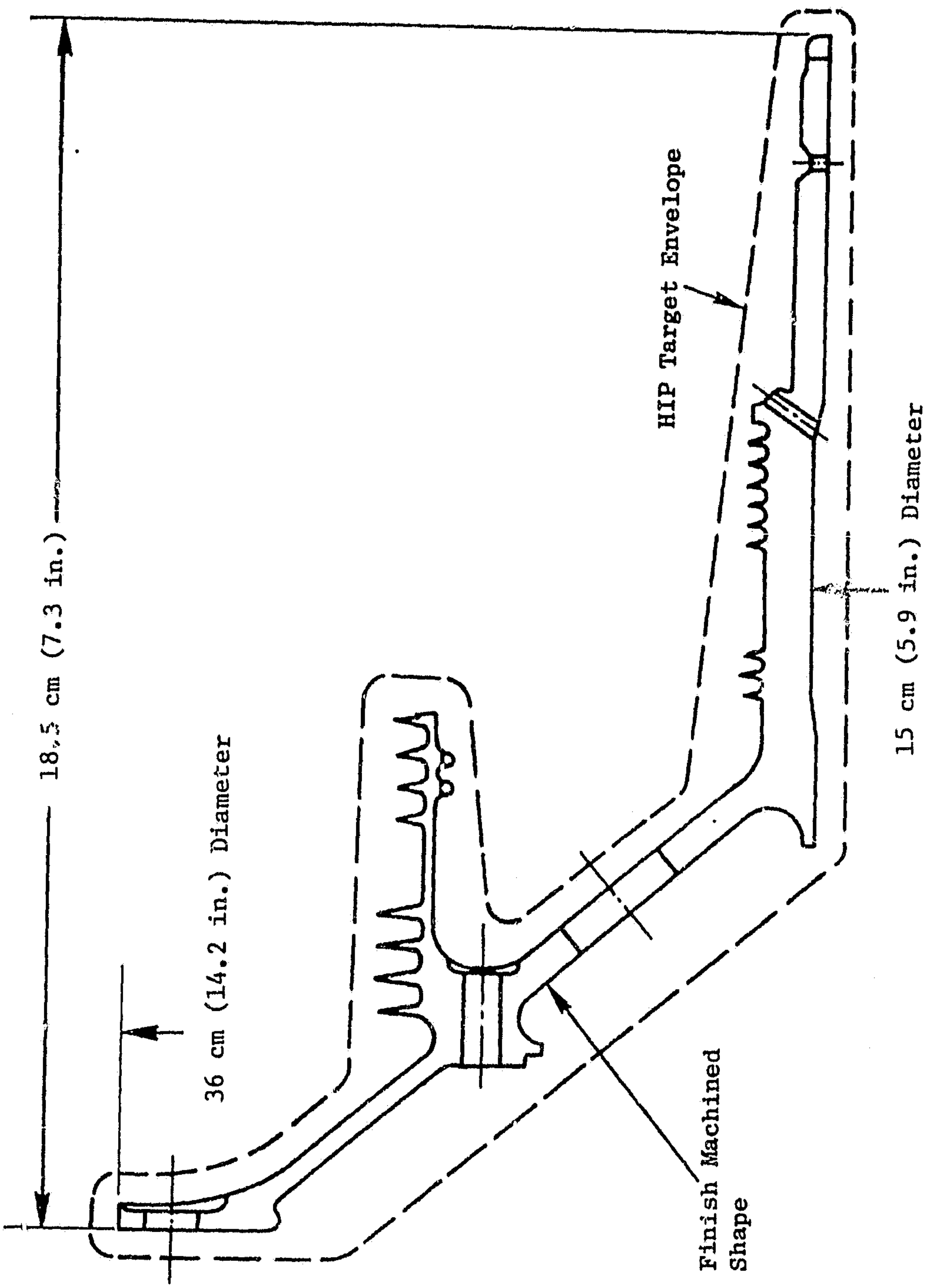


Figure 3. CF6-50 HPTR Rear Shaft.

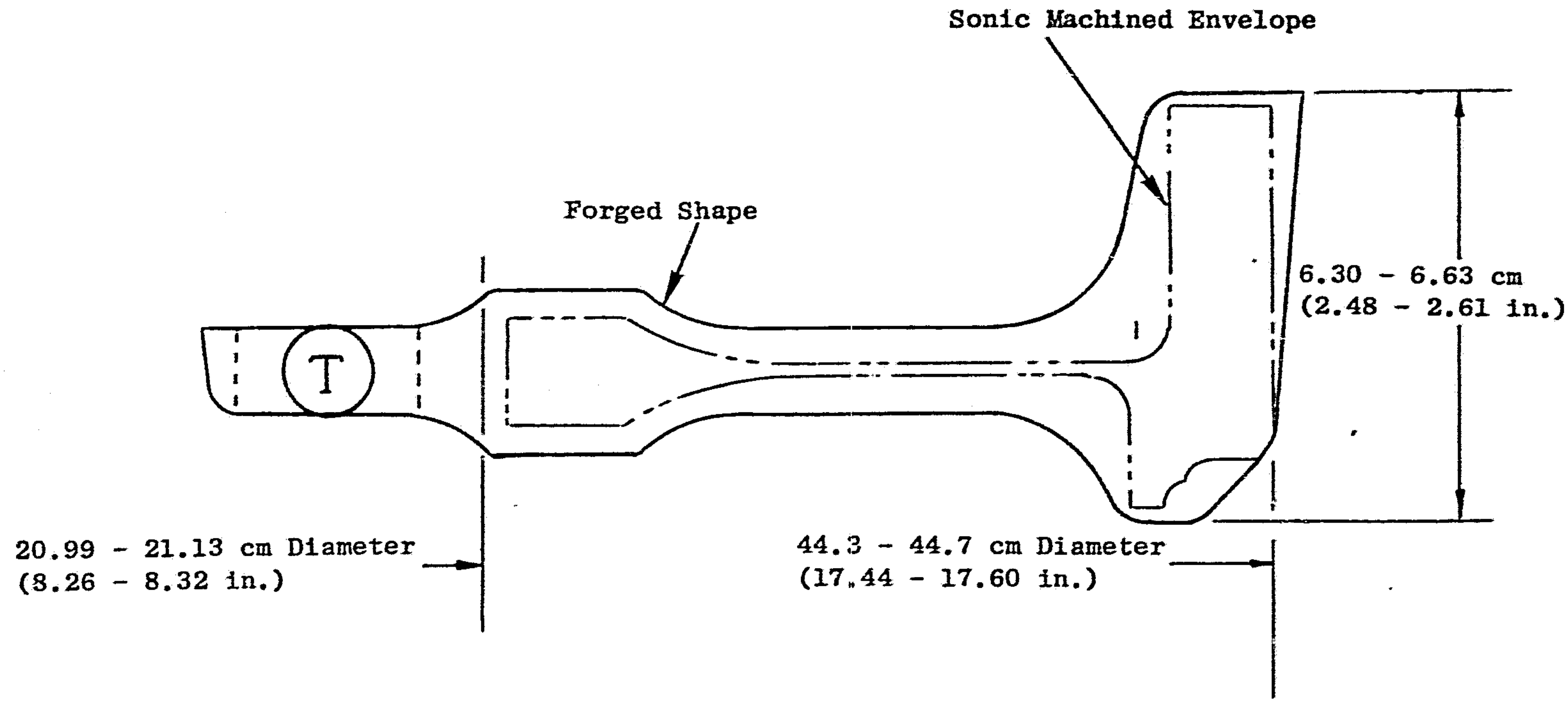


Figure 4. CFM56 Stage 5 through 9 Compressor Rotor Disk Forging Configuration.

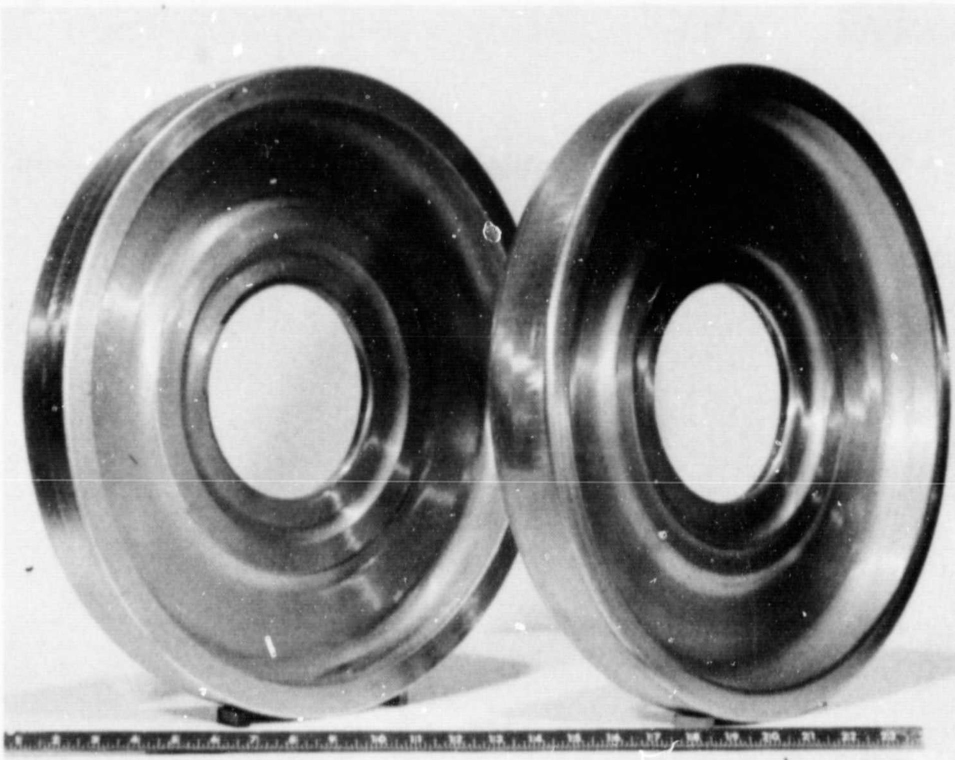

Figure 5. CFM56 Compressor Disks in Sonic Machined Configuration After Hot Die Forging From Powder Preforms.

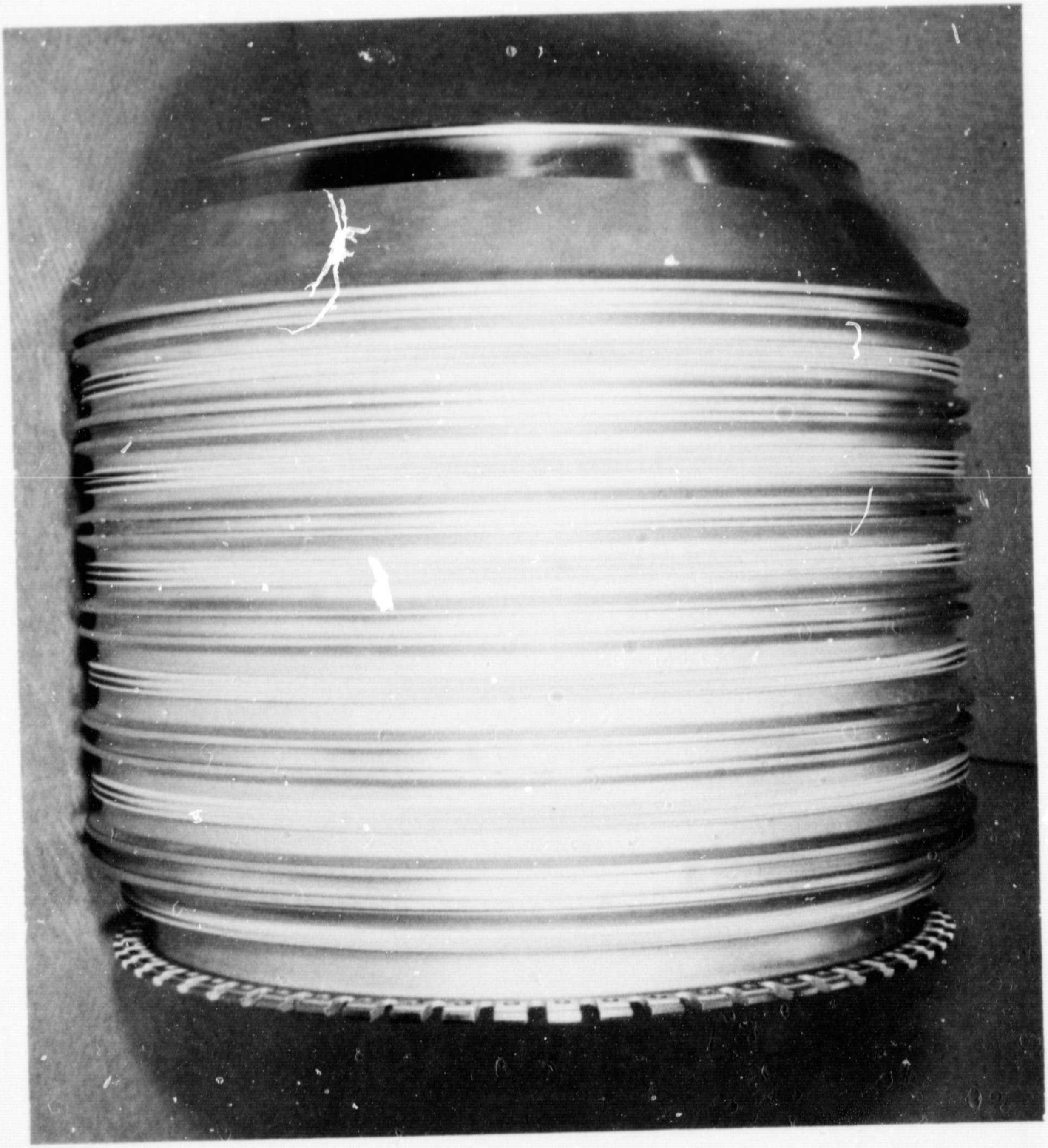

Figure 6. CFM56 Engine Inertia Welded and Finish-Machined Compressor Spool Prior to Engine Test.

Table II. Mechanical Property Requirements High Pressure Turbine Rotor Aft Shaft.

| Minimum Tensile Properties | | | |
|---|---|---|---|
| Room Temperature - MPa (ksi) | | | |
| Ultimate Strength | 0.2% Yield Strength | Elongation, % | Red. Area, % |
| 1496 (217) | 1145 (166) | 10 | 12 |
| 649° C (1200° F) - MPa (ksi) | | | |
| 1365 (198) | 1041 (151) | --- | --- |

Minimum Stress Rupture Properties

| Temperature, ° C (° F) | Stress MPa (ksi) | Life, hours | Elongation, % |
|---|---|---|---|
| 649 (1200) | 965 (140) | 25 | 2 |

Table III. Mechanical Property Requirements CFM56 Stage 5 Through 9 Compressor Disks.

**Minimum Tensile Properties**

| Heat Treated Section Thickness, mm (in.) | Ultimate Strength, MPa (ksi) | 0.2% Yield Strength, MPa (ksi) | Elongation, % | Red. Area, % |
|---|---|---|---|---|
| Room Temperature - MPa (ksi) | | | | |
| Up to 35.6 (1.4) | 1544 (224) | 1207 (175) | 10 | 12 |
| >35.6 to 45.0 (1.4 to 1.8) | 1524 (221) | 1179 (171) | 10 | 12 |
| 649° C (1200° F) - MPa (ksi) | | | | |
| Up to 35.6 (1.4) | 1427 (207) | 1117 (162) | 8 | 10 |
| >35.6 to 46.0 (>1.4 to 1.8) | 1407 (204) | 1089 (158) | | |

**Minimum Stress Rupture Properties**

| Temperature, ° C (° F) | Stress MPa, ksi | Life, hours | Elongation, % |
|---|---|---|---|
| 649 (1200) | 1030 (150) | 25 | 2 |

Figure 7 shows a typical "C" cycle engine operation sequence for the CFM56 engine. Each cycle includes conditions simulating ground idle, takeoff, aircraft descent, and thrust reverse conditions. These are the high stress and low cycle fatigue conditions of most concern for component life. The cruise condition is not specifically evaluated in "C" cycle testing since it is a steady state, relatively low stress condition and does not impact low cycle fatigue life. Two thousand of these "C" cycles were run in the MATE CFM56 engine test for a total running time of about 643 hours as indicated in Table IV.

Table IV. Total Engine Test Time for Stage 5 Through 9 Compressor Spool in Engine 502-008 - Build 2.

| Engine Build No. | Total Running, hours:minutes | "C" Cycles |
|---|---|---|
| Prior Builds(1) | 170:19 | --- |
| 008-2C(2) | 473:11 | 2000 |
| Total | 643:30 | 2000 |

(1)Miscellaneous Tests
(2)MATE "C" Cycle Engine Test

Figure 8 shows a typical "C" cycle for the CF6-50 engine. This cycle includes ground idle, takeoff, climb, descent, and thrust reverse engine operating conditions. One thousand and one of these cycles were run during the CF6-50 engine test of the HPTR aft shaft. This was accomplished in a total of 252 hours of running time during this test.

Table V presents the temperature and stress levels for the CFM56 Stage 3 compressor disk produced during the idle and takeoff conditions of the "C" cycle test. These are the minimum and maximum temperature/stress conditions encountered during the "C" cycle testing. Data for the CF6-50 high pressure turbine rotor aft shaft are given in Table VI. The stresses in the shaft are much lower than those in the disk and this is typical of shaft designs of this type.

Both the CFM56 and CF6-50 engine tests conducted here were representative of typical engine tests conducted for Federal Aviation Agency certification of these engines or of new components intended for use in these engines.

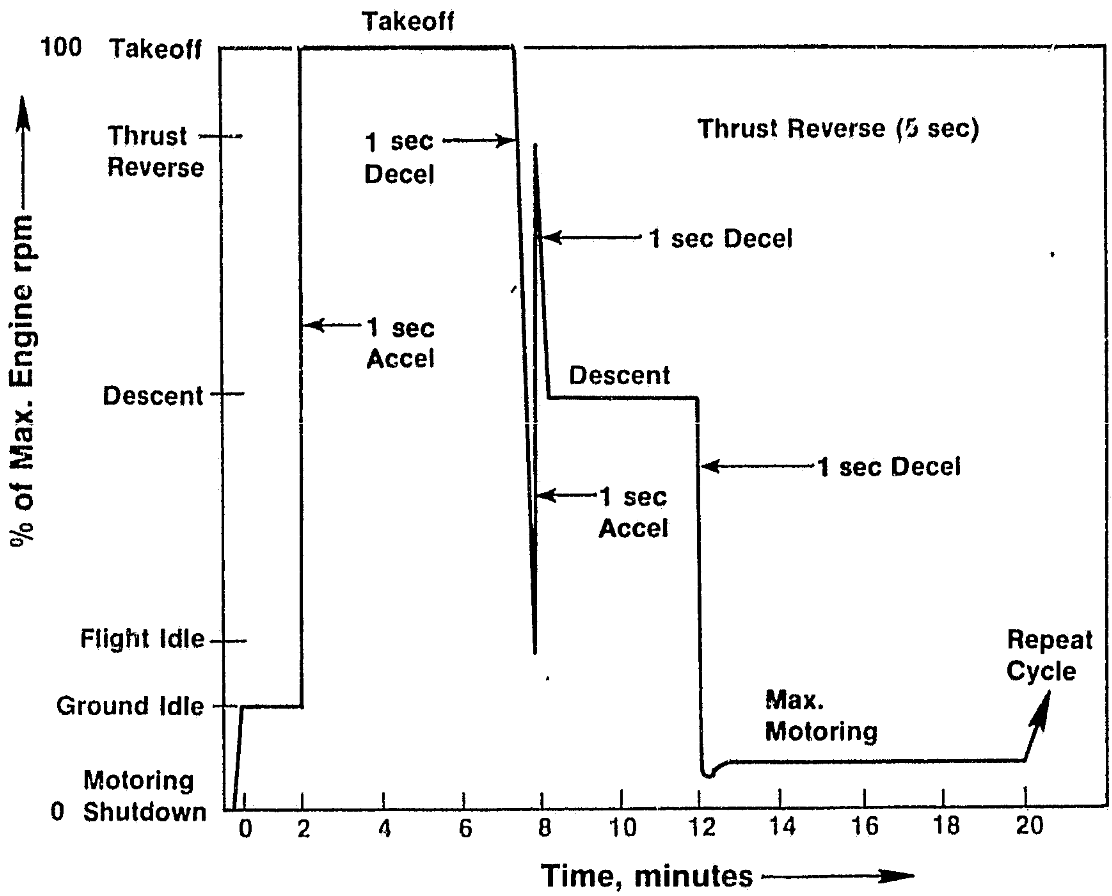


Figure 7. CFM56 Simulated Service "C" Cycle.

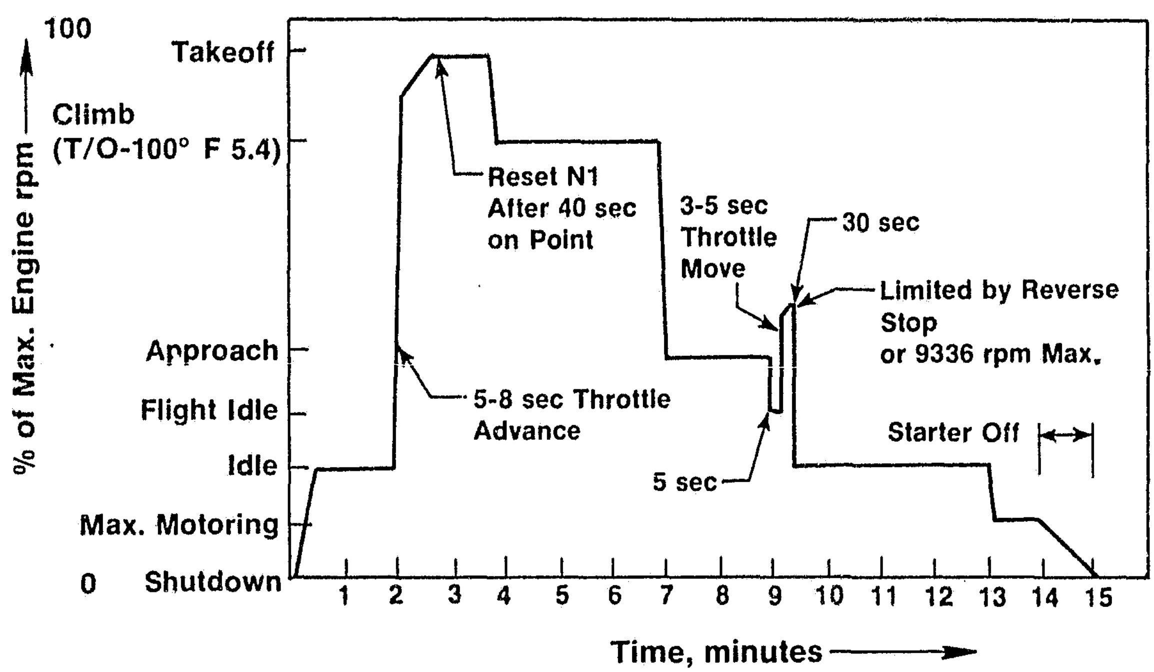


Figure 8. CF6-50 Simulated Service "C" Cycle.

Table V. CFM56 Stage 5 Compressor Disk Engine Test.

| | Condition | |
|---|---|---|
| | Idle | Takeoff |
| Disk Average Temperature, ° C (° F) | 97.0 (206) | 252.0 (486) |
| Average Tangential Stress, MPa (ksi) | 358.5 (52) | 770.0 (111.7) |
| Maximum Disk Temperature, ° C (° F) | 133.0 (271) | 397.0 (747) |
| Bore Stress, MPa (ksi) | 455.0 (66) | 1092.0 (158.4) |

Table VI. CF6-50 Aft High Pressure Turbine Shaft Engine Test Conditions.

| | Condition | |
|---|---|---|
| | Idle | Takeoff |
| Average Shaft Temperature, ° C (° F) | 117 (243) | 366 (691) |
| Average Tangential Stress, MPa (ksi) | 55 (7.9) | 162 (23.5) |
| Maximum Shaft Temperature, ° C (° F) | 186 (367) | 543 (1010) |

## 4.0 ENGINE POSTTEST ANALYSIS

The engine posttest analysis of the CFM56 compressor disk and the CF6-50 HPTR aft shaft included visual examination before and after cleaning, fluorescent penetrant inspection, and dimensional inspection of specified dimensions.

The visual examination and fluorescent penetrant inspection of both parts showed no indications of defects or other distress resulting from the engine test. The engine posttest dimensional analyses of the Stage 5 CFM56 compressor disk and the CF6-50 high pressure turbine disk are given in Appendix A. The dimensional variations observed were within normal engine posttest experience for similar engine tested components. The CFM56 spool, including the Stage 5 MATE disk was returned for further engine tests outside the scope of the MATE program since the René 95 disk is Bill of Material in this engine. Although the CF6-50 HPTR aft shaft was judged acceptable for further engine use, it was retired from service since René 95 is no longer Bill of Material in the CF6-50 engine.

A photogrpah of the CFM56 engine compressor spool after test is shown in Figure 9. The CF6-50 HPTR aft shaft is shown in Figure 10 after 1000 cycles of engine testing.

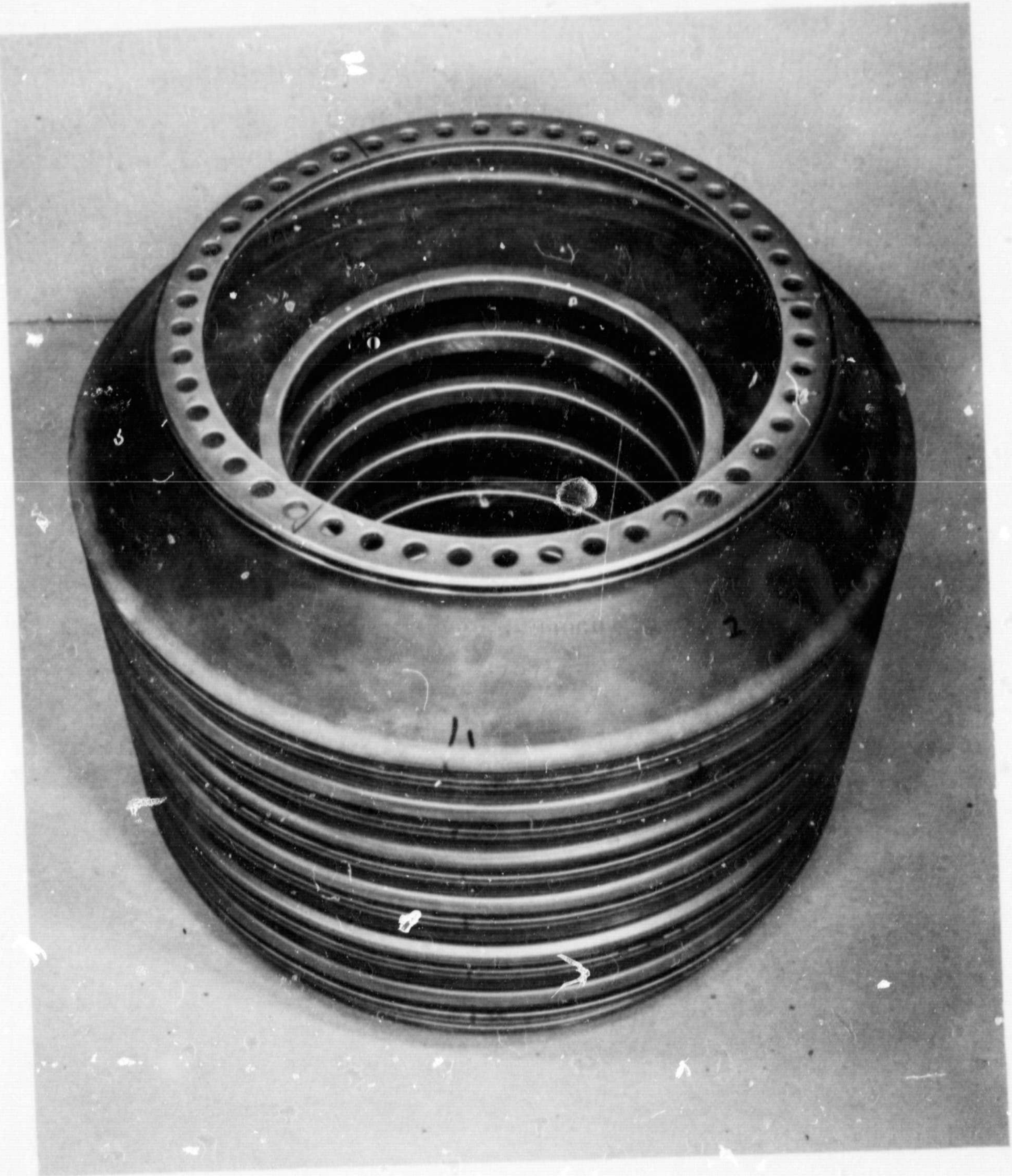

Figure 9. CFM56 Compressor Spool, S/N 9707, After Engine Test for 2000 "C" Cycles.

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Figure 10. CF6-50 HPTR Aft Shaft After 1001 "C" Cycle Engine Test.

## 5.0 CONCLUSIONS

The results of these engine tests and the engine posttest analyses demonstrated that both the CFM56 René 95 HIP plus forged compressor disk and the as-HIP CF6-50 high pressure turbine rotor aft shaft performed successfully in their respective engines. As planned, these engine tests followed the same test plan as that required for new engine models and for certification of new components. The René 95 Stage 5 through 9 compressor disks now are Bill of Material on the CFM56 engine and processes developed during the MATE program are used in their manufacture.

## APPENDIX A - DIMENSIONAL ANALYSIS

The dimensional analysis data for the René 95 CF6-50 high pressure turbine aft shaft are presented in Table A-I. The dimensional analysis results for the CFM56 Stage 5 compressor disk are presented in Table A-II. Figure A-1 shows the diametral locations of the measurement points for the HPTR shaft. The minimum seal and bearing diameters are given in Note 2 in this figure, and it can be seen that all dimensions were within original drawing requirements indicating that no significant wear occurred during the engine test.

Table A-I. Dimensional Data for the CF6-50 HPTR Shaft.

| Location[1] | Measurement No. | Diameter in. | Diameter mm | Drawing Requirement in. (mm) |
|---|---|---|---|---|
| Oil Seal Teeth, H | 1 | 6.751 | 171.48 | 6.749 - 6.751 (171.42 - 171.48) |
| | 2 | 6.751 | 171.48 | |
| | 3 | 6.751 | 171.48 | |
| | 4 | 6.751 | 171.48 | |
| | 5 | 6.751 | 171.48 | |
| | 6 | 6.751 | 171.48 | |
| Air Seal Teeth, E | 1 | 11.081 | 281.46 | 11.078 - 11.084 (281.38 - 281.53) |
| | 2 | 11.082 | 281.48 | |
| | 3 | 11.082 | 281.48 | |
| | 4 | 11.079 | 281.41 | |
| | 5 | 11.079 | 281.41 | |
| | 6 | 11.080 | 281.43 | |
| Air Seal Teeth, F | 1 | 10.880 | 276.35 | 10.880 - 10.884 (276.35 - 276.45) |
| | 2 | 10.881 | 276.38 | |
| | 3 | 10.882 | 276.40 | |
| | 4 | 10.882 | 276.40 | |
| | 5 | 10.882 | 276.40 | |
| | 6 | 10.882 | 276.40 | |
| No. 5 Bearing Journal, A | 1 | 6.1845 | 157.09 | 6.180 - 6.194 (156.97 - 157.33) |
| | 2 | 6.1850 | 157.10 | |
| | 3 | 6.1850 | 157.10 | |
| | 4 | 6.1850 | 157.10 | |
| | 5 | 6.1848 | 157.09 | |
| | 6 | 6.1848 | 157.09 | |

[1] See Figure A-1 for diametral locations

[2] Minimum seal dimensions after test are:

| Diameter | Dimension in. | (mm) |
|---|---|---|
| H | 6.575 | (167.00) |
| E | 11.058 | (280.87) |
| F | 10.860 | (275.84) |
| A | 6.170 | (156.72) |

Table A-II. Dimensional Data for the Stage 5 CFM56 Compressor Disk.

| Location | Measurement No. | Diameter in. | Diameter mm | Before Test(1) in. | Before Test(1) mm |
|---|---|---|---|---|---|
| Maximum Rim Diameter, Forward | 1 | 17.195 | 436.75 | 17.196 | 436.78 |
| | 2 | 17.195 | 436.75 | 17.196 | 436.78 |
| | 3 | 17.195 | 436.75 | 17.196 | 436.78 |
| | 4 | 17.195 | 436.75 | 17 196 | 436.78 |
| Maximum Rim Diameter, Aft | 1 | 17.1965 | 436.79 | 17.196 | 436.78 |
| | 2 | 17.197 | 436.80 | 17.196 | 436.78 |
| | 3 | 17.196 | 436.78 | 17.196 | 436.78 |
| | 4 | 17.1965 | 436.79 | 17.196 | 436.78 |

(1)Drawing requirement is 17.193 - 17.197 in. (436.70 - 436.80 mm)

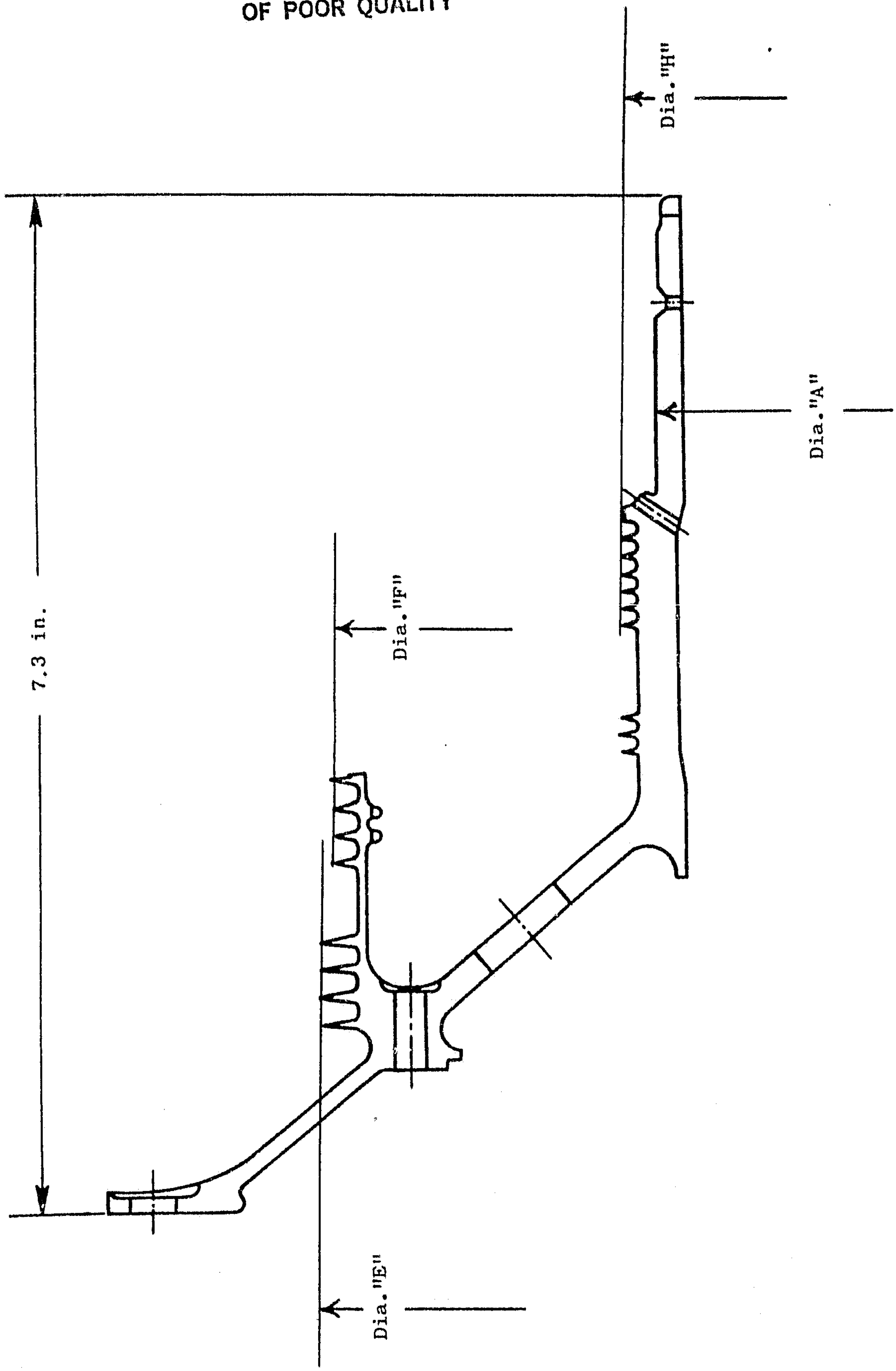


Figure A-1. CF6-50 HPTR Shaft Dimensional Location.